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RESEARCH MEMORANDUM

TRANSONIC FLIGHT TESTS TO DETERMINE THE EFFECT OF THICKNESS RATIO AND PLAN-FORM MODIFICATION ON THE ZERO-LIFT DRAG OF A 45° SWEPTBACK WING

By William B. Pepper, Jr., and Sherwood Hoffman

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NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS

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TRANSONIC FLIGHT TESTS TO DETERMINE THE EFFECT OF THICKNESS RATIO AND PLAN-FORM MODIFICATION ON THE ZERO-LIFT DRAG OF A 45° SWEPTBACK WING

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SUMMARY

Rocket-powered models were flown at transonic speeds to determine the effect of the wing-thickness-ratio variation on the zero-lift drag coefficient of a conventional sweptback plan-form wing and a composite plan-form wing, derived from the conventional wing, mounted on a fuselage of fineness ratio 10. The conventional plan-form wing had a sweepback angle of 45° along the quarter-chord line, an aspect ratio of 6.0, and a taper ratio of 0.6. Three conventional plan-form wings were tested having thickness ratios of 9 percent, 6 percent, and a linear taper in thickness from 9 percent at the fuselage center line to 3 percent at the wing tip.

Three composite plan-form wings of aspect ratio 4.06 having a taper ratio of 0.7 for the outer panel and 0.3 for the inner panel were tested.

The wing-plus-interference pressure-drag coefficient of both plan forms investigated varied approximately linearly with the square of the mean thickness ratio (based on the root-mean-square thickness ratios of the conventional wings) at low supersonic Mach numbers and for the lower thickness ratios on the order of 6 percent.

The total drag of the configuration having the 9-percent-thick conventional plan-form wing was reduced by modifying the plan form to that of the composite wing for Mach numbers above 1.07. A small increase in the total drag was observed when the same plan-form modification was applied to the configurations having the 6-percent-thick wings and the tapered 9- to 3-percent-thick wings.

The experimental parameter for the pressure-drag thickness ratio of a wing with interference for the conventional plan-form wing showed good agreement with a theoretical first-order approximation, calculated

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by means of a generalization of the linear source-sink solution for sweptback tapered wings, in a range of Mach numbers from 1.0 to 1.3. Between Mach numbers of 1.3 and 1.4, the theory rapidly diverged from the experimental values. More experimentation is required to substantiate the theory.

INTRODUCTION

As part of a general transonic research program of the National Advisory Committee for Aeronautics to determine the aerodynamic properties of promising aircraft configurations, rocket-propelled models were tested in free flight to determine the effect of variations in thickness ratio and plan-form modification on zero-lift drag for a sweptback wing.

The original wing, called the conventional plan-form wing, had a sweepback angle of 45° along the quarter-chord line, an aspect ratio of 6.0, a taper ratio of 0.6, and the NACA 65A-series airfoil section in the free-stream direction. The three airfoil thickness ratios that were tested were 9 percent, 6 percent, and a taper in thickness from 9 percent at the fuselage center line to 3 percent at the wing tip.

In an attempt to improve the conventional plan-form wing structurally for transonic and supersonic flight, the conventional plan-form wing was modified inboard of the 40-percent-semispan station resulting in a lower aspect ratio and more taper for the modified wing. The inboard panel of the modified wing, called the composite plan-form wing for convenience, was formed by shearing back that portion of the airfoil to the rear of the maximum thickness and inboard of the 40-percent-semispan station, maintaining the leading- and trailing-edge ordinates, and filling the triangular space thus formed with flat sections. The three composite plan-form wings which were tested had thickness distributions corresponding to the conventional plan-form wings.

Flight tests covered a continuous Mach number range from 0.8 to 1.4. The Reynolds number, based on the mean aerodynamic chord of the conventional wing, varied from approximately 3.9×10^{6} to 8.3×10^{6} throughout the test range.

SYMBOLS

b	wing span, in.
C_{D_T}	drag coefficient of total configuration based on S_W

C_{D_W} drag coefficient of wing-plus-interference based on S_E

$C_{D_{W_P}}$ wing pressure drag

M Mach number

R Reynolds number based on mean aerodynamic chord of conventional plan-form wing

S_{W_e} exposed wing plan-form area, sq ft

S_W total wing plan-form area, sq ft

Y spanwise station, in.

t local wing thickness, in.

c local wing chord at spanwise station Y, in.

c_o exposed wing root, in.

$\overline{(t/c)}$ root-mean-square thickness ratio

$$\overline{(t/c)} = \left[\frac{\int_{c_o}^{b/2} \left(\frac{t}{c}\right)^2 c \, dY}{\int_{c_o}^{b/2} c \, dY}\right]^{1/2}$$

r fuselage radius, in.

x wing or body station, in.

y wing ordinate, in.

MODELS

The two wing plan forms tested in the present investigation were a conventional 45° sweptback wing and a composite plan-form wing. The wings were mounted on a fuselage of fineness ratic 10 so that the leading edges of the wings intersected the fuselage surface at its maximum diameter. The fuselage coordinates are given in table I. For convenience, the models are listed as the following:

Model		Basic thickness ratio, $(\overline{t/c})$, percent		Mean thickness ratio, $(\overline{t/c})$, percent	
		Root	Tip		
A (ref. 1)	Conventional plan-form wings	9	9	9	
B		9	3	6.66	
C		6	6	6	
D	Composite plan-form wings	9	9	9	Assumed effective thickness of pressure drag surfaces
E		9	3	6.66	
F		6	6	6	

The conventional sweptback wings (figs. 1(a) and 2(a)) had a sweepback angle of 45° along the quarter-chord line, a taper ratio of 0.6, an aspect ratio of 6.0, and NACA 65A-series airfoils in the free-stream direction. The thickness ratios tested were 9 percent for model A, a taper in thickness from 9 percent at the fuselage center line to 3 percent at the wing tip for model B, and 6 percent for model C. The coordinates of the 65A-series sections used are given in tables II, III, and IV.

The three composite plan-form wing models shown in figures 1(b) and 2(b) were derived from the previously described conventional plan-form wing models by shearing back that portion of the airfoil to the rear of the maximum thickness and inboard of the 40-percent-semispan station, maintaining the leading- and trailing-edge ordinates of the 65A-series airfoils, and filling the triangular space thus formed with flat sections. Model D was derived from model A, model E from model B, and model F from model C. The total frontal area of each conventional plan-form wing and the corresponding composite plan-form wing was the same since the maximum wing thickness was not changed by the modification. The composite plan-form wings had an aspect ratio of 4.06 based on the total wing area and a taper ratio varying from approximately 0.7 for the outer wing panel to 0.3 for the inner panel.

The models were constructed of mahogany with 0.05-inch-thick steel inlays in the wings. The models were stabilized in flight by the swept-back wing in the wing plane and by two flat-plate fins in the plane perpendicular to the wing.

TESTS AND MEASUREMENTS

The models were tested at the Langley Pilotless Aircraft Research Station at Wallops Island, Va. Each model was propelled by a two-stage rocket system and launched from a rail launcher. The first stage or booster consisted of a 5-inch, lightweight, high-velocity aircraft rocket motor that served to accelerate the model from zero velocity to high subsonic speeds. After drag separation of the booster and model, a 3.25-inch Mk 7 rocket motor, which was installed in the fuselage, accelerated the model to supersonic speeds. Tracking instrumentation, consisting of a CW Doppler velocimeter radar set and an NACA modified SCR 584 tracking radar unit, was used to determine the deceleration and trajectory of the model during coasting flight. A survey of atmospheric conditions at the time of each launching was made through radiosonde measurements from an ascending balloon.

The Reynolds number of the tests, based on the mean aerodynamic chord of the conventional plan-form wing, varied from 3.7×10^6 at $M = 0.8$ to 8.3×10^6 at $M = 1.40$. (See fig. 3.)

Values of the total drag coefficient were calculated as in reference 1. The variations of wing-plus-interference drag coefficient, based on exposed wing area, were obtained by subtracting the drag coefficient of the body and two fins (ref. 2) from the total drag coefficients of the wing-body-fin configurations tested, or

$$C_{D_W} = \left(C_{D_{wing+body+2\ fins}} - C_{D_{body+2\ fins}}\right) S_W/S_{W_e}$$

where $C_{D_{wing+body+2\ fins}}$ and $C_{D_{body+2\ fins}}$ are based on S_W.

The wing-plus-interference pressure drag was obtained by subtracting an average friction drag coefficient of 0.004 from the total wing drag.

The magnitude of the error in total drag coefficient was established from the test results of three identical wing-body models in reference 1 and was based on the maximum deviation found between curves faired through the experimental points. At flight Mach numbers from 0.8 to 0.93 and 1.02 to 1.25, the probable errors based on the conventional plan-form wing area are believed to be within the following limits:

C_{D_T} . . . . ± 0.0004
C_{D_W} . . . . ± 0.001
$C_{D_{W_P}}$ . . . . ± 0.002
M . . . . ± 0.005

Because the slope of the drag curve changes rapidly near a Mach number of 1.0, the errors in drag coefficient are larger than in the foregoing table and are of the order given in the following table:

C_{D_T} . . . . ±0.0017
C_{D_W} . . . . ±0.004

RESULTS AND DISCUSSION

The variations of total drag coefficient with Mach number for the models having the conventional plan-form wings (models A, B, and C) and for the fuselage with two fins (ref. 2) are given in figure 4(a). From a comparison of the results, it is evident that a large reduction in C_{D_T} was obtained by reducing the thickness ratio of the 9-percent wing to 6 percent or by tapering the thickness from 9 percent at the fuselage center line to 3 percent at the wing tip. The subsonic drag coefficients of models A, B, and C were approximately the same up to a Mach number of 0.94.

The variations of C_{D_T} with M for the models with the composite plan-form wings in figure 4(b) also show that decreasing the thickness ratio of model D either uniformly along the semispan or by tapering the thickness toward the wing tip reduced the total drag coefficient at supersonic speeds. Although subsonic data were not obtained for model F, it is believed that the subsonic drag from model F was about the same as that obtained from models D and E since all the composite plan-form wings had the same wing area.

The total drag coefficients in figure 4(c) are based on the total plan-form area of the conventional wing in order to show the effect on the total drag force of modifying the conventional plan-form wing to the composite plan-form wing. From a comparison of the variations of C_{D_T} with M, the results show that the plan-form modification of the 9-percent wing (models A to D) reduced the total drag above $M = 1.07$. A small increase in drag, however, was obtained from the plan-form modification of the 6-percent-thick wing (models C to F) and the wing tapered in thickness from 9 percent to 3 percent (models B to E).

Figure 5 shows the variations of wing-plus-interference drag coefficient (based on the exposed plan-form area of each wing) with Mach number for all the wings tested. Since the aspect ratios of the conventional and composite plan-form wings were not the same and their plan forms were different, no direct comparison between their wing drag coefficients was made. The drag-rise Mach numbers of all the wings tested varied from 0.94 to 0.96 and did not show any consistent trends with thickness ratio.

The values of the pressure drag coefficient in figure 6 were estimated from figure 5 by subtracting from the coefficients of the supersonic wing drag a friction drag coefficient of 0.004, which was obtained from the average values of C_{D_W} of all the wings tested at subsonic Mach numbers. In plotting the drag parameter for the composite wings, the thickness ratios corresponding to those of the conventional wings were used since the thickness distribution of the sloping surfaces were unaltered by the modification. The wing-plus-interference pressure drag coefficients of each plan form investigated are shown in figure 6 to vary approximately linearly with the square of the mean thickness ratio at Mach numbers of 1.05, 1.15, and 1.25 except for the 9-percent-thick conventional wing at $M = 1.05$ and $M = 1.15$. A comparison of the flight data with wind-tunnel data from reference 3 for the conventional plan-form wing alone and with unpublished wind-tunnel data for the composite plan-form wing alone in figure 6 shows that $C_{D_{W_P}}$ obtained for wings with interference from flight tests was of the same order as that obtained from the tunnel tests of the wings alone.

Figure 7 shows the wing-plus-interference pressure drag coefficients for the conventional and composite wings based on the conventional wing area and plotted against the conventional-wing mean thickness ratios. If the pressure on the wings was unaltered by the modification, the pressure drag coefficients would not change if plotted in this manner. For the Mach numbers greater than 1.05 and for the 6-percent and 9- to 3-percent tapered-in-thickness wings, the modification does not change the wing pressure drag. For the 9-percent-thick wings, however, the modification reduces $C_{D_{W_P}}$ considerably at Mach numbers above 1.05 so that a large part of the beneficial effect of the modification shown in figure 4(c) was to alleviate the unfavorable drag characteristics of the 9-percent-thick wing. The beneficial effect that the modification caused on the 9-percent-thick wing may be due to favorable wing-body interference and to an improvement in the wing drag characteristics.

The variations of the pressure-drag thickness-ratio parameter $C_{D_{W_P}}/100(\overline{t/c})^2$ with Mach number in figure 8 for the wings tested were obtained from the slopes of straight lines drawn between the experimental points in figure 6. The curves apply to the lower thickness ratios in the order of 6 percent because of the nonlinearities of the 9-percent wings. A comparison between these curves shows that the values of the pressure-drag thickness-ratio parameter of the conventional plan-form wing were greater than the values of the parameter obtained from the composite plan-form wing above $M = 1.04$ when the parameter for both wings is based on the conventional wing $(\overline{t/c})$. When the drag coefficient of the composite wing is based on the exposed area of the conventional wing, as was shown in figure 7, the curve for the composite wing would be approximately the same as the curve shown in figure 8 for the conventional wing.

Figure 8 also shows a comparison between the experimental variations of $C_{D_{W_P}}/100(\overline{t/c})^2$ for the conventional plan-form wing with interference and the theoretical variations of the parameter as determined from the method described in reference 4. The theoretical variations of the parameter were calculated from a generalization of the linear source-sink method for sweptback, tapered wings using a 10-slope airfoil contour to approximate the 65A-series airfoils used herein. Good agreement between experiment and theory was obtained for the conventional wing from a range of Mach numbers of 1.0 to 1.30. From $M = 1.30$ to $M = 1.40$, where the Mach number line is very near the leading edge of the wing, the theoretical values of the parameter increase rapidly and cannot be used to predict the pressure-drag thickness-ratio parameter of the wing. More experimentation is required, however, before the theory can be fully substantiated.

CONCLUSIONS

The effects of wing-thickness-ratio variation on the zero-lift drag of a conventional 45° sweptback wing plan form and a composite plan-form wing that was derived from the conventional plan-form wing, mounted on a fuselage of fineness ratio 10, have been determined by tests of rocket-propelled models in free flight. The tests covered a Mach number range varying from 0.8 to 1.40 at corresponding Reynolds numbers of 3.9×10^6 to 8.3×10^6 based on the mean aerodynamic chord of the conventional wing. The following conclusions were made:

1. The wing-plus-interference pressure drag coefficient of both plan forms tested varied approximately linearly with the square of the mean thickness ratio (based on the root-mean-square ratios of the conventional plan-form wings) for a range of Mach numbers from 1.05 to 1.25 and for the lower thickness ratios on the order of 6 percent.

2. The total drag of the configuration having the 9-percent-thick conventional plan-form wing was reduced by modifying the plan form to that of the composite wing for Mach numbers above 1.07. A small increase in the total drag was observed when the same plan-form modification was applied to the configurations having the 6-percent-thick wings and the tapered 9- to 3-percent-thick wings.

3. The experimental parameter for the pressure-drag thickness ratio of a wing with interference for the conventional plan-form wing showed good agreement with a theoretical first-order approximation, calculated by means of a generalization of the linear source-sink solution of the wing pressure drag, in a range of Mach numbers from 1.0 to 1.3. Between Mach numbers of 1.3 and 1.4, the theory rapidly diverged from the experimental values. Further experimentation is required to substantiate the theory.

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2. Pepper, William B.: The Effect on Zero-Lift Drag of an Indented Fuselage or a Thickened Wing-Root Modification to a 45° Sweptback Wing-Body Configuration as Determined by Flight Tests at Transonic Speeds. NACA RM L51F15, 1951.

3. Morrison, William D., Jr., and Fournier, Paul G.: Effects of Spanwise Thickness Variation on the Aerodynamic Characteristics of 35° and 45° Sweptback Wings of Aspect Ratio 6. Transonic-Bump Method. NACA RM L51D19, 1951.

4. Beane, Beverly: The Characteristics of Supersonic Wings Having Biconvex Sections. Jour. Aero. Sci., vol. 18, no. 1, Jan. 1951, pp. 7-20.

TABLE I

FUSELAGE COORDINATES

x, in.	r, in.
0	0
.4	.185
.6	.238
1.0	.342
2.0	.578
4.0	.964
6.0	1.290
8.0	1.577
12.0	2.074
16.0	2.472
20.0	2.772
24.0	2.993
28.0	3.146
32.0	3.250
36.0	3.314
40.0	3.334
44.0	3.304
48.0	3.219
52.0	3.037
56.0	2.849
60.0	2.661
64.0	2.474
66.7	2.347
Nose radius: 0.040 in.	

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TABLE II

COORDINATES OF THE NACA 65A009 AIRFOIL

x/c (percent)	y/c (percent)
0	0
.5	.688
.75	.835
1.25	1.065
2.5	1.460
5.0	1.964
7.5	2.385
10.0	2.736
15.0	3.292
20.0	3.714
25.0	4.036
30.0	4.268
35.0	4.421
40.0	4.495
45.0	4.485
50.0	4.377
55.0	4.169
60.0	3.874
65.0	3.509
70.0	3.089
75.0	2.620
80.0	2.117
85.0	1.594
90.0	1.069
95.0	.544
100.0	.019
Leading-edge radius: 0.575 percent c	
Trailing-edge radius: 0.021 percent c	

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TABLE III

COORDINATES OF THE NACA 65A006 AIRFOIL

x/c (percent)	y/c (percent)
0	0
.5	.464
.75	.563
1.25	.718
2.5	.981
5.0	1.313
7.5	1.591
10.0	1.824
15.0	2.194
20.0	2.474
25.0	2.687
30.0	2.842
35.0	2.945
40.0	2.996
45.0	2.992
50.0	2.925
55.0	2.793
60.0	2.602
65.0	2.364
70.0	2.087
75.0	1.775
80.0	1.437
85.0	1.083
90.0	.727
95.0	.370
100.0	.013
Leading-edge radius: 0.229 percent c	
Trailing-edge radius: 0.014 percent c	

TABLE IV

COORDINATES OF THE NACA 65A003 AIRFOIL

x/c (percent)	y/c (percent)
0	0
.5	.234
.75	.284
1.25	.362
2.5	.493
5.0	.658
7.5	.796
10.0	.912
15.0	1.097
20.0	1.236
25.0	1.342
30.0	1.420
35.0	1.472
40.0	1.498
45.0	1.497
50.0	1.465
55.0	1.402
60.0	1.309
65.0	1.191
70.0	1.053
75.0	.897
80.0	.727
85.0	.549
90.0	.369
95.0	.188
100.0	.007
Leading-edge radius: 0.057 percent c	
Trailing-edge radius: 0.0068 percent c	

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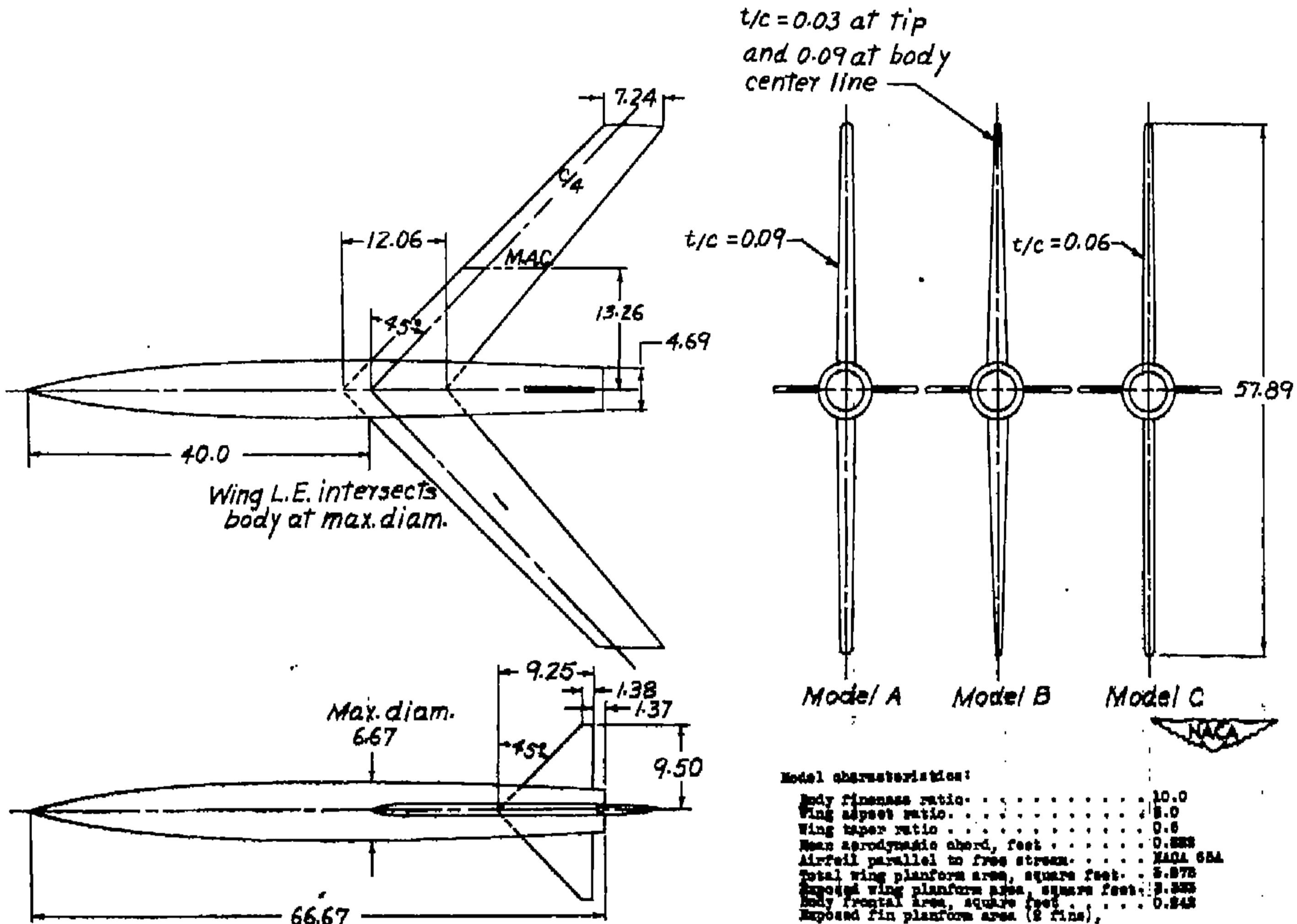


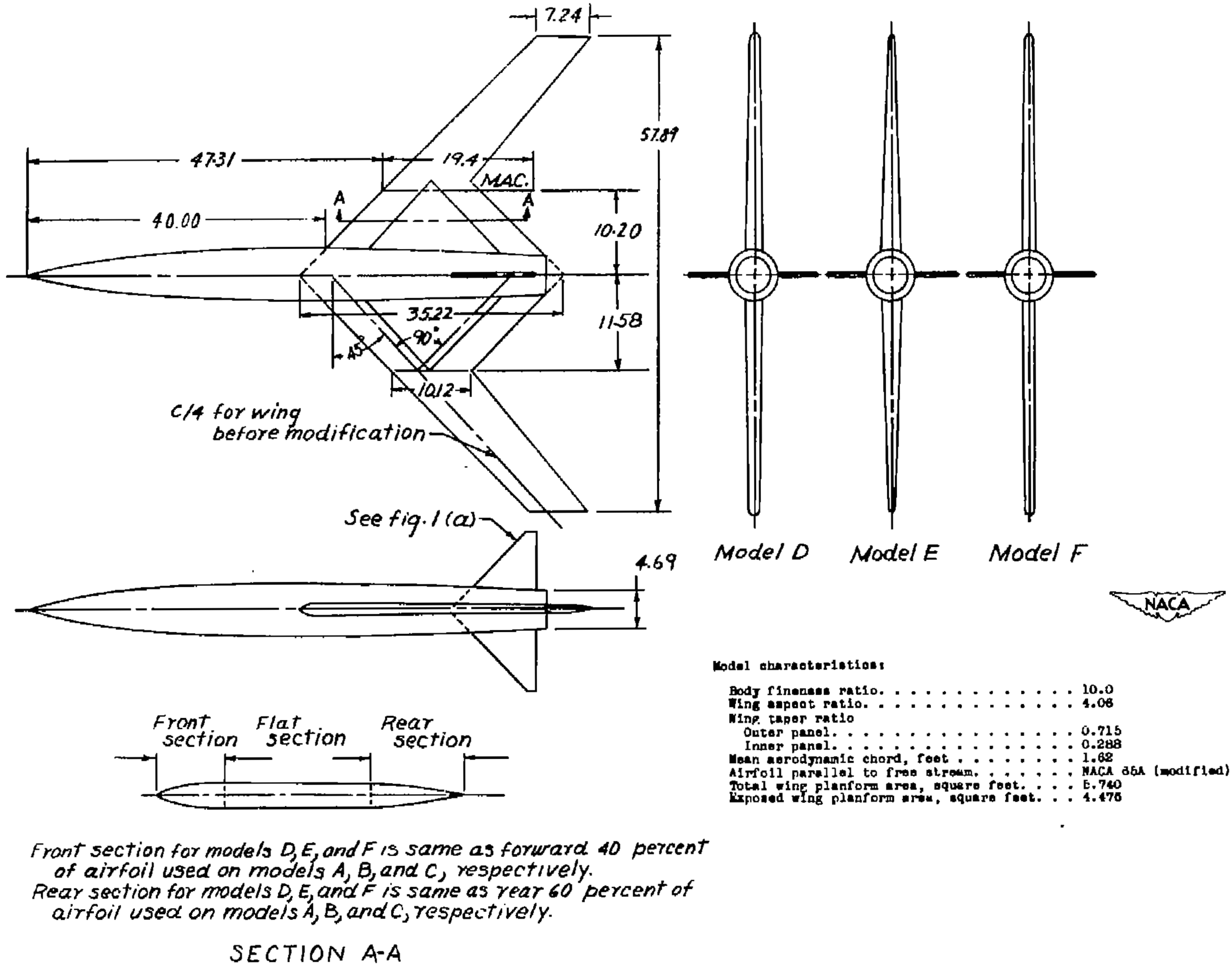
Model characteristics:

Body fineness ratio	10.0
Wing aspect ratio	6.0
Wing taper ratio	0.6
Mean aerodynamic chord, feet	0.8[illegible]
Airfoil parallel to free stream	NACA 65A
Total wing planform area, square feet	3.878
Exposed wing planform area, square feet	2.3[illegible]
Body frontal area, square feet	0.242
Exposed fin planform area (2 fins), square feet	0.465

Fins are flat plates and 0.091 inch thick with 0.045-inch radius at edges.

(a) Models with conventional plan-form wing.

Figure 1.- General arrangement and dimensions of test models. All dimensions are in inches.

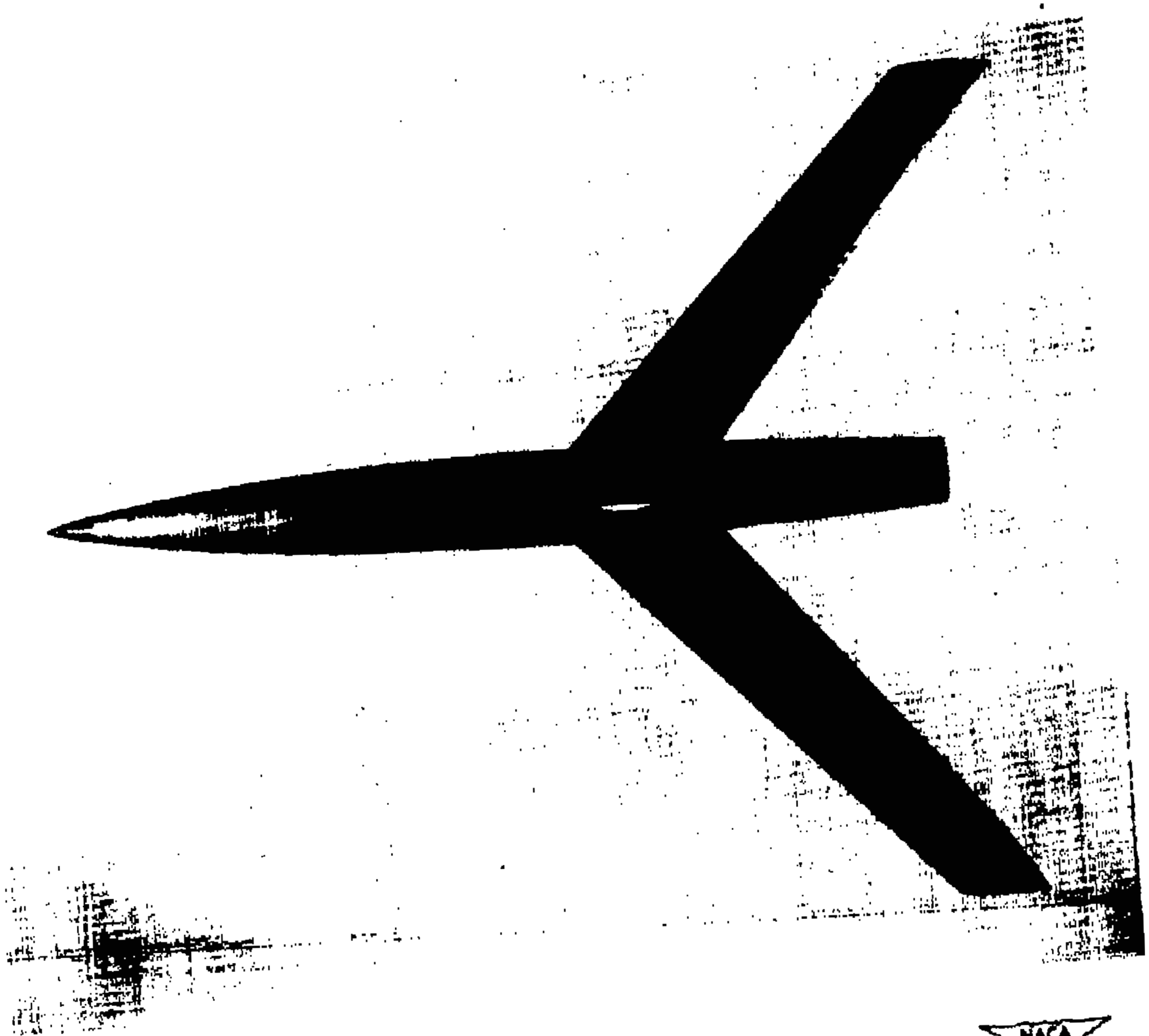


Model characteristics:

Body fineness ratio	10.0
Wing aspect ratio	4.06
Wing taper ratio	
Outer panel	0.715
Inner panel	0.288
Mean aerodynamic chord, feet	1.62
Airfoil parallel to free stream	NACA 65A (modified)
Total wing planform area, square feet	5.740
Exposed wing planform area, square feet	4.476

(b) Models with composite plan-form wing.

Figure 1.- Concluded.



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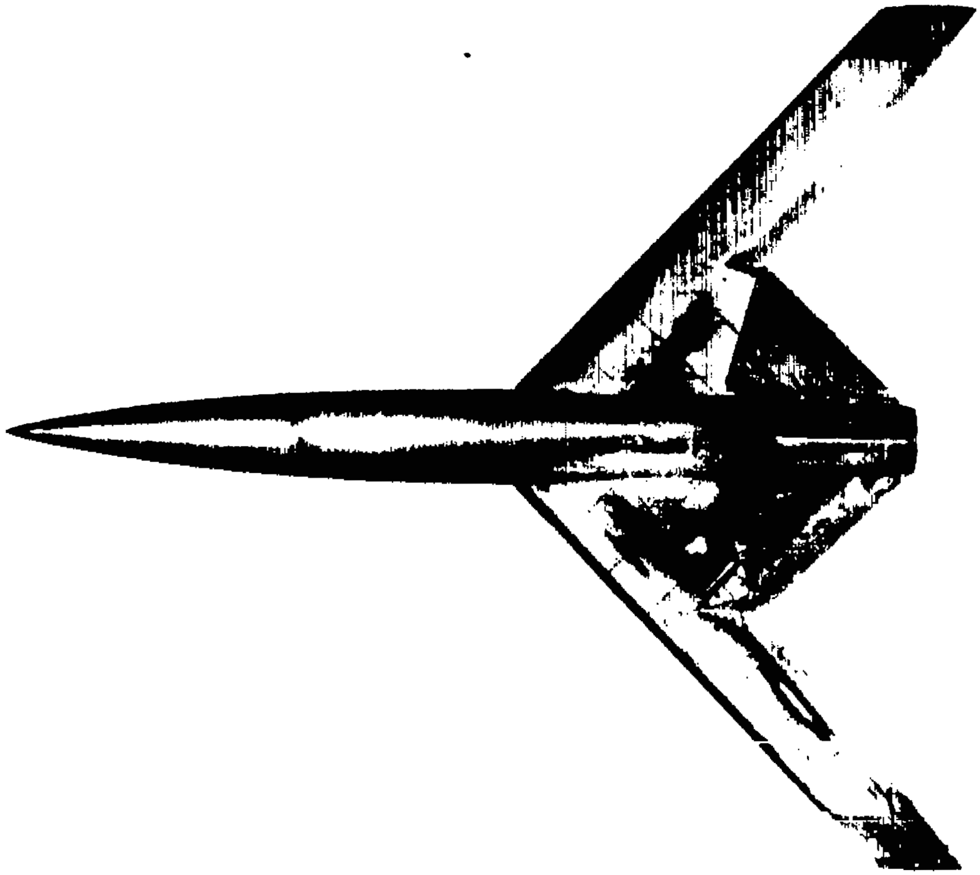
(a) Model with conventional plan-form wing.

Figure 2.- Photographs of models showing plan-form views of the conventional and composite wings.



(b) Model with composite plan-form wing.

Figure 2.- Concluded.

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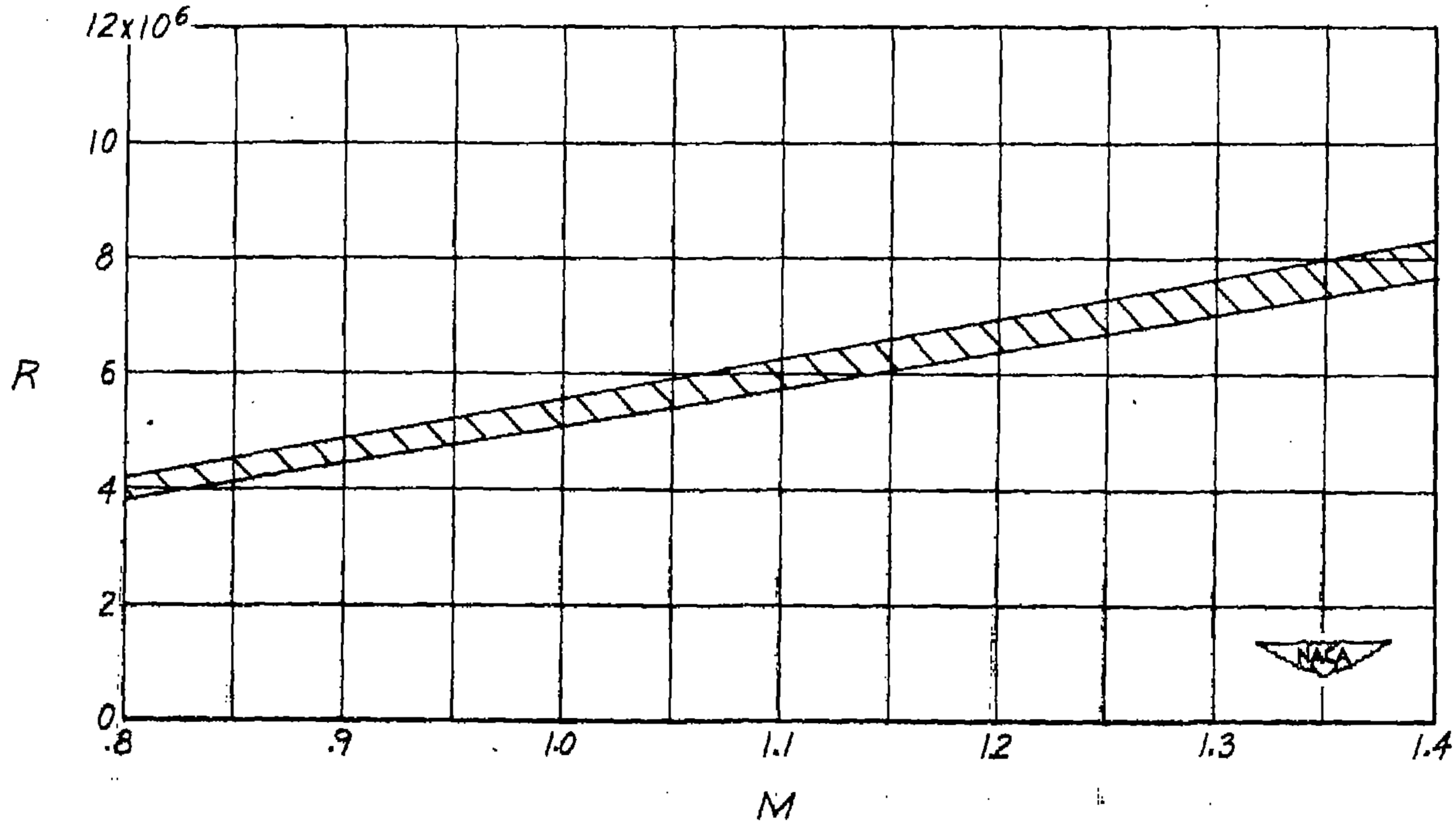
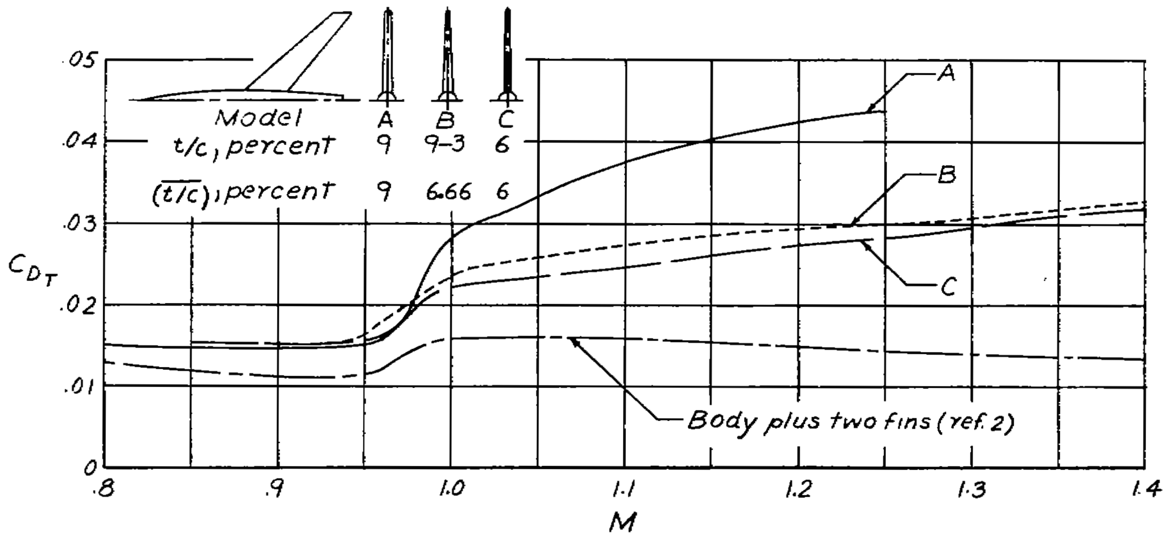
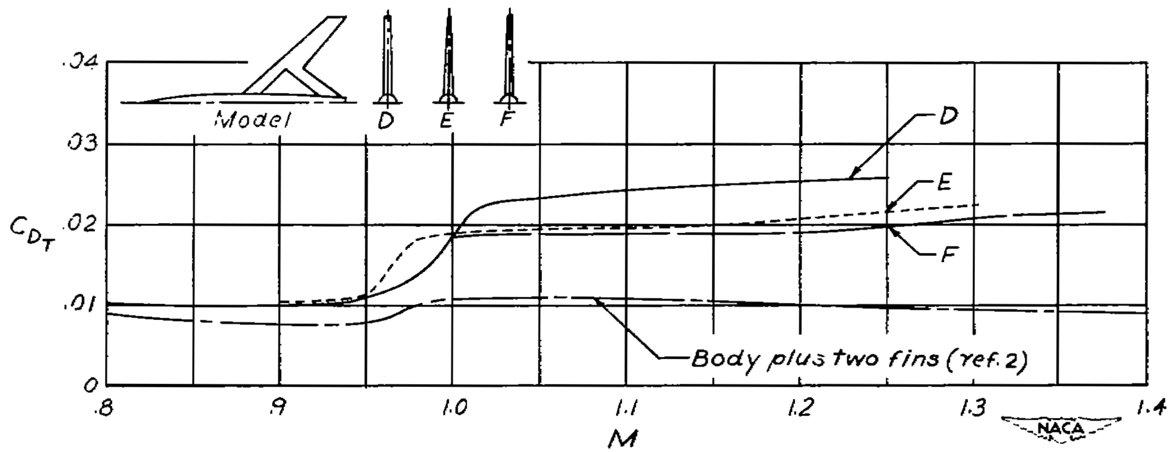


Figure 3.- Variation of Reynolds number with Mach number for models tested. R is based on the mean aerodynamic chord of conventional plan-form wing.

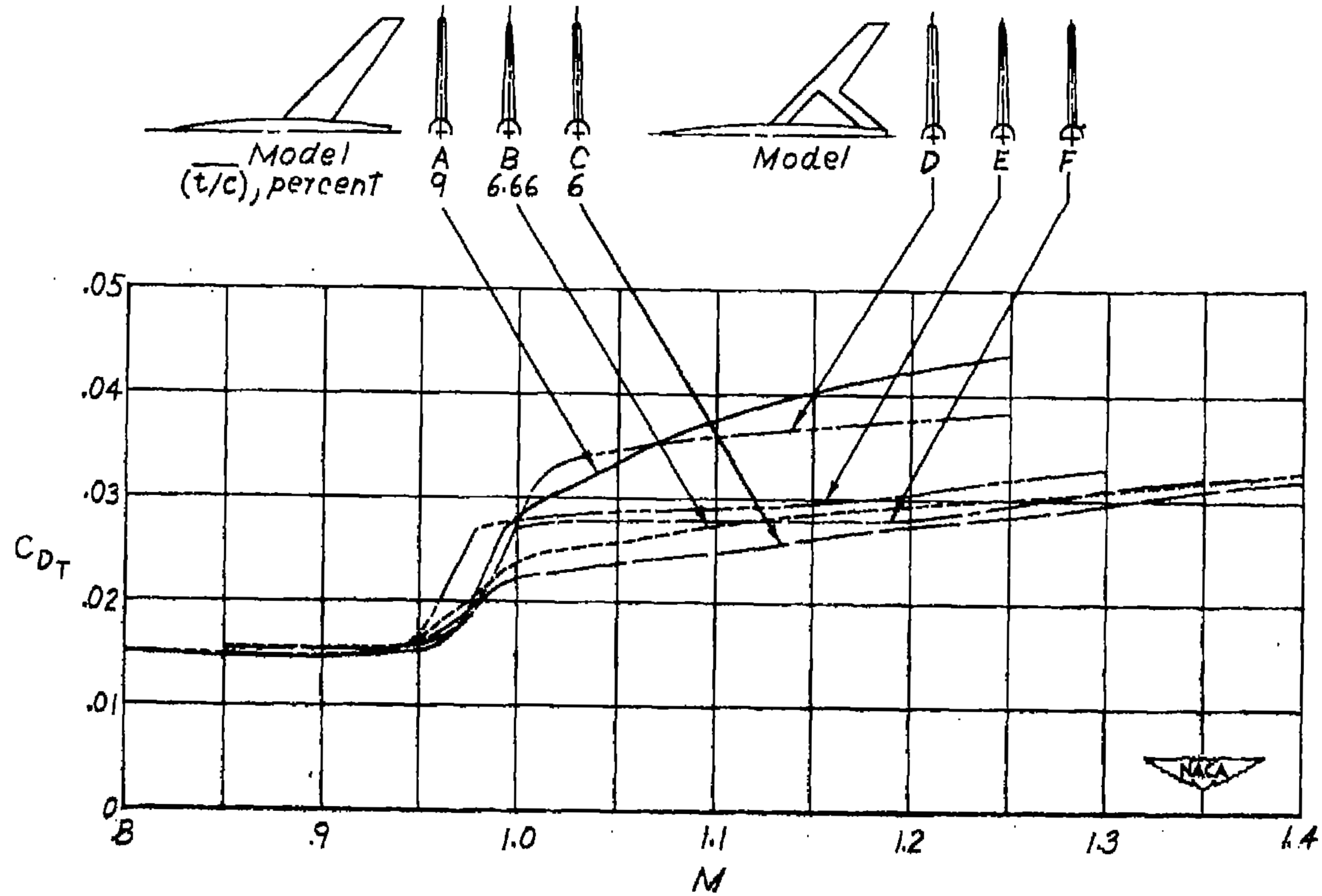


(a) Models with conventional plan-form wing. C_{D_T} is based on S_W of conventional wing.



(b) Models with composite plan-form wing. C_{D_T} is based on S_W of composite wing.

Figure 4.- Variations of total configuration drag coefficients with Mach number showing the effect of wing thickness on the zero-lift drag of models tested.



(c) Drag-force comparison of all models tested. C_{D_T} is based on S_W of conventional plan-form wing.

Figure 4.- Concluded.

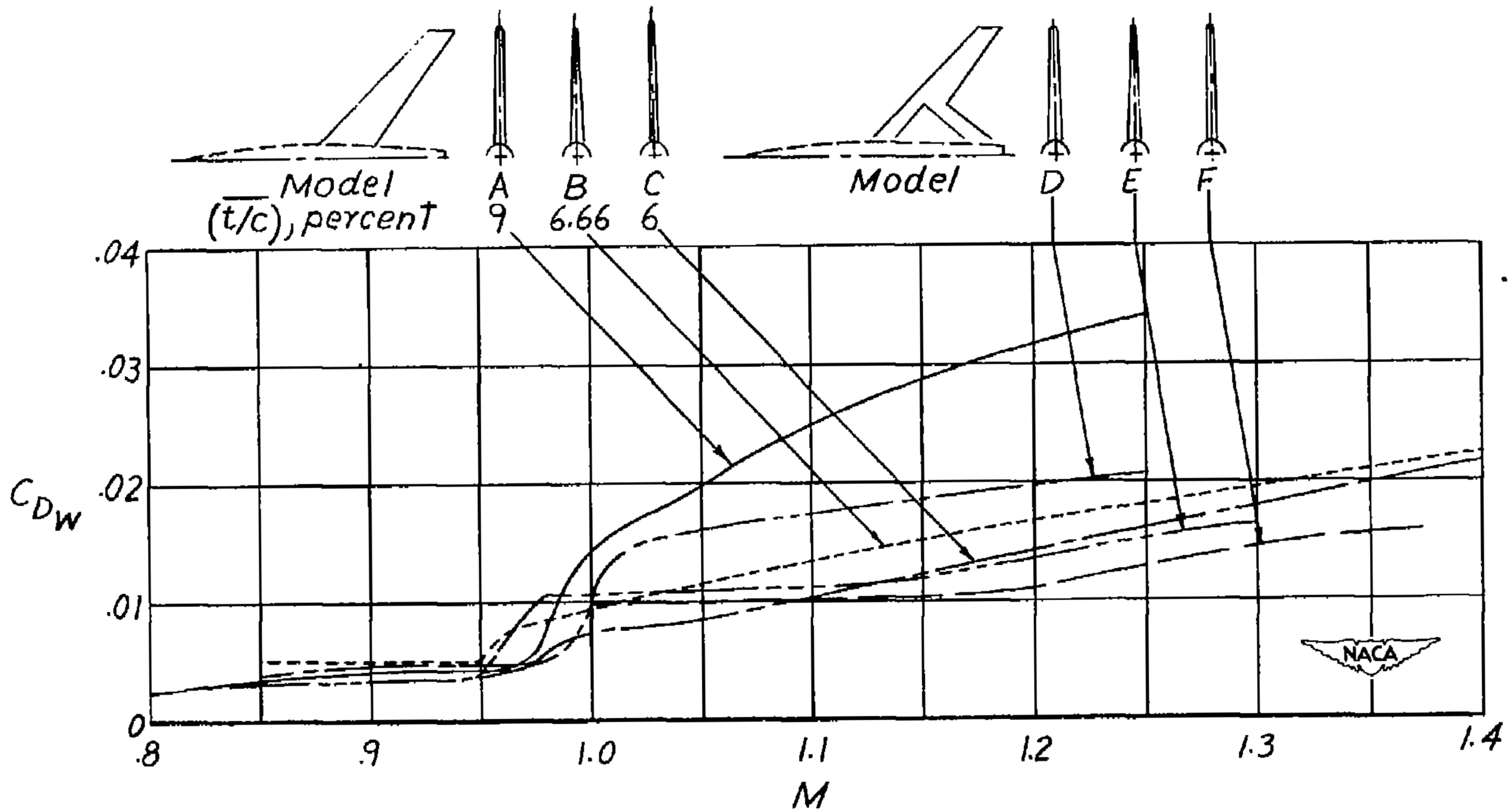


Figure 5.- Variations of wing-plus-interference drag coefficients with Mach number for the conventional and composite wings of various thickness ratios. C_{D_W} is based on the exposed wing plan-form area of each wing tested.

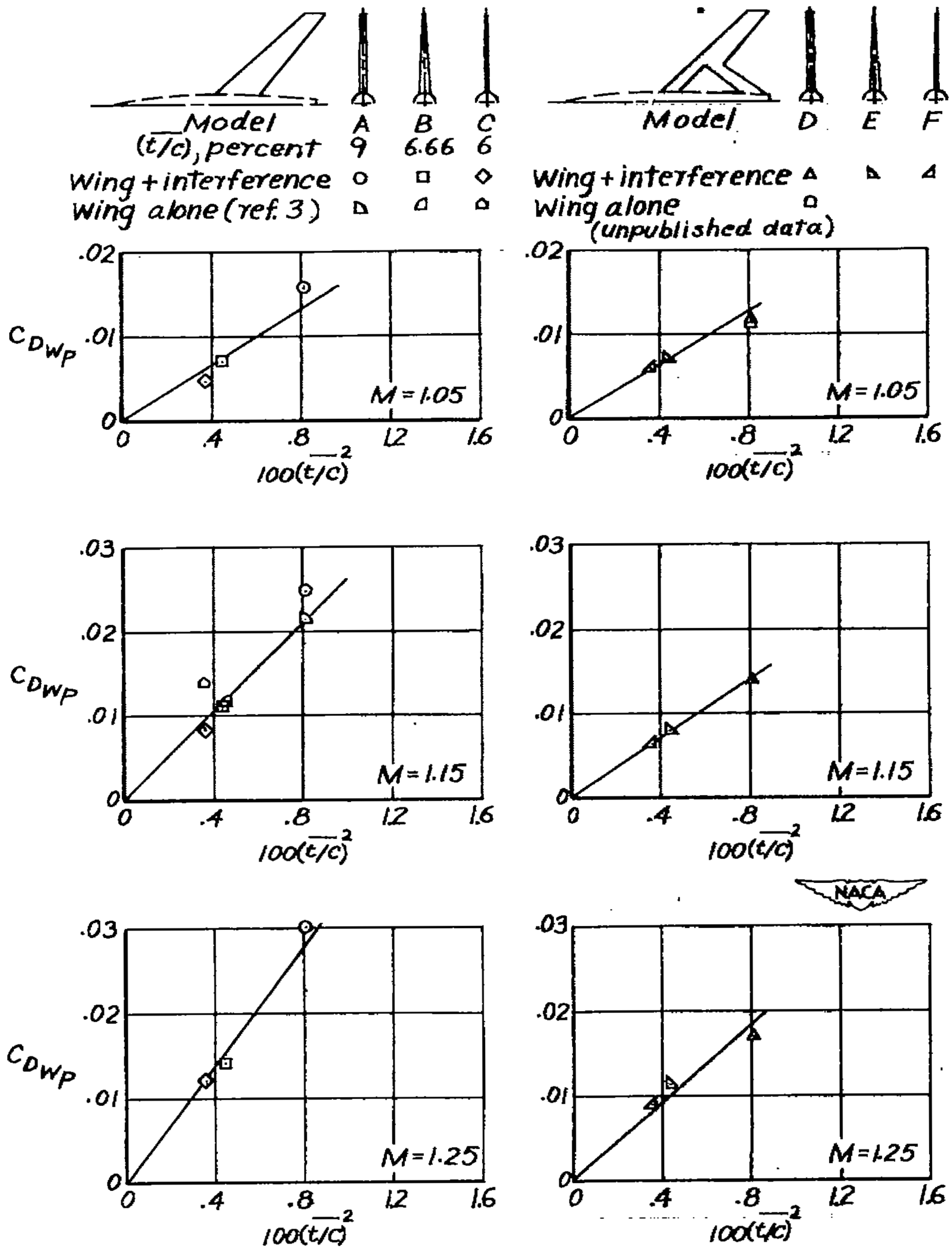


Figure 6.- Variations of pressure drag coefficients of conventional and composite plan-form wings with the square of the mean thickness ratio at Mach numbers of 1.05, 1.15, and 1.25. The value of $\overline{(t/c)}^2$ is based on the conventional plan-form wings and $C_{D_{W_P}}$ is based on the exposed wing area of each wing tested.

SECURITY INFORMATION

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